SIGNIFICANCE OF CONSIDERING SOIL-STRUCTURE INTERACTION EFFECTS ON SEISMIC DESIGN OF UNBRACED BUILDING FRAMES RESTING ON SOFT SOILS

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ABSTRACT

The current study carries out a comprehensive critical review on available and well-known research studies in the area of seismic behaviour of braced and unbraced building structures affected by soil-structure interaction (SSI). Based on the current review outcomes, it has become apparent that considering effects of SSI in seismic design of braced building structures is not necessary and assuming fixed-base structure is deemed to be conservative. However, SSI effects can amplify the lateral deflections and corresponding inter-storey drifts of unbraced building structures founding on soft grounds, forcing the structure to behave in the inelastic range, resulting in severe damage of the building structures. Consequently, seismic design procedure of unbraced building structures founding on soft soils without taking into account detrimental influences of SSI cannot adequately assure structural sufficiency and safety for the benefit of the community.

Keywords: Soil-Structure Interaction (SSI), Seismic Behaviour, Performance Level, Soft Soil Deposits, Unbraced Building Frames, Free Field Motion.

1 INTRODUCTION

The Mexico City earthquake in 1985 (Gazetas and Mylonakis, 1998) and Christchurch-New Zealand earthquake in 2011 (Bray & Dashti, 2012) evidently demonstrate the significance of site local properties on the seismic response of structures. The mentioned earthquakes as well as many other examples clearly depict the significance of amplification of rock motions at the base level of un-braced building structures founding on relatively soft grounds. Soil-Structure Interaction (SSI) is the structural response of dynamic loading due to the soils motion influencing the structure and the structures motion influencing the soil. In more recent years, it has become clear that the effects of SSI on structural systems become increasingly significant when the structures are founded on soft soils (Gazetas and Mylonakis, 1998; Maheshwari and Sarkar, 2011). In addition, available research suggests that SSI's are substantial when the soil's average shear wave velocity is less than 600 m/s, particularly when supporting un-braced buildings (Veletsos and Meek, 1974; Tabatabaiefar *et al*., 2012a).

Structures resting on soft grounds experience a motion different from the free-field motion of the supporting soil resulting in a feedback loop. This loop involves the structure responding to the motion of the soil which in turn responds to the motion of the structure. The structural response of such an interaction is determined by the soil characteristics, dynamic load properties and the structural design (Fatahi *et al*., 2011). Typical seismic analysis ignores this SSI effect and analyses the structures foundations to behave rigidly with the soil. This assumption is fine for average sized structures supported on bedrock as it has become apparent that the free field motion of the rock is barely influenced by the presence of the structure i.e. SSI is not a factor of the structure's seismic response. However, for structures supported on relatively soft grounds, the mentioned hypothesis loses its validity as performance levels of the buildings under seismic loads may alter from life safe to near collapse or even total collapse (Samali *et al*., 2011; Tabatabaiefar *et al*., 2011).

2 METHODS OF MODELLING SOIL MEDIUM FOR SOIL-STRUCTURE INTERACTION ANALYSIS

The way the soil medium is modelled during SSI analysis is integral in accurately representing the inelastic structural response and the nonlinear behaviour of the underneath supporting soil due to seismic excitation. At present, there are three general methods available to represent the soil medium for soil-structure interaction analysis of structures, namely, Winkler Model (Spring Model), Lumped Parameter on Elastic Half Space and Numerical Methods.

The Winkler foundation model (Figure 1) uses an independent series of discrete, narrowly spaced linear springs to simulate the underlying soil medium. The main issue in this method is the assumption that the soil behaves in linear stress–strain manner. It is also difficult to determine the spring's stiffness to fairly represent the soil and the independence of each spring further faults the model. Dutta and Roy (2002) denoted that the use of this model should ideally only be employed during analysis of a structure when the only other alternative is to consider the structure as being fixed base.

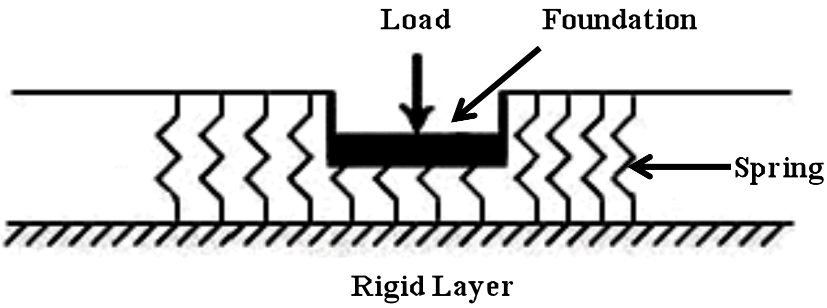


Figure 1: Winkler foundation model.

Lumped Parameter on Elastic Half Space involves placing three translational and three rotational springs along three reciprocally perpendicular axes and three rotational degrees of freedom about the same axes below each foundation in the structure. Dashpots are also added to the system to consider soil dampening effects. The idea of this method is to represent the spring's stiffness as being dependent on the frequency of the forcing function. Different researchers (Lysmer, 1965; Gazetas, 1991; Wolf, 1994) suggested stiffness and dampening values for the various springs and dashpots.

The model parameters developed by Wolf (1994) allowed the Lumped Parameter method more accurately model the effect of frequency dependent soil-flexibility on the structural behaviour compared to the Winkler method which considered the soil-flexibility to be frequency independent (Figure 2). It was however concluded by Bowles (1996) that the Lumped Parameter method was not sufficiently detailed tomodel more complex structural problems.

The advent of powerful computers has significantly changed computational aspects. As the scope of numerical methods has been wider than analytical methods, the use of finite element method (FEM) or finite difference method (FDM) has become more popular for studying complex and complicated interactive behaviour. Both methods produce a set of algebraic equations which may be identical for the two methods to be solved. According to Cundall (1976), it is pointless to argue about the relative merits of finite element or finite difference approaches as the resulting equations are the same. Finite element programs often combine the element matrices into a large global stiffness matrix, while this is not usually done with finite difference because it is relatively more efficient to regenerate the finite difference equations at each step.

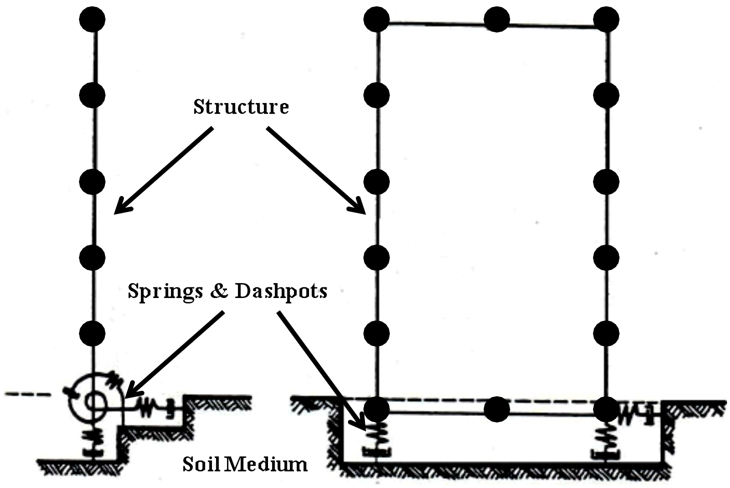
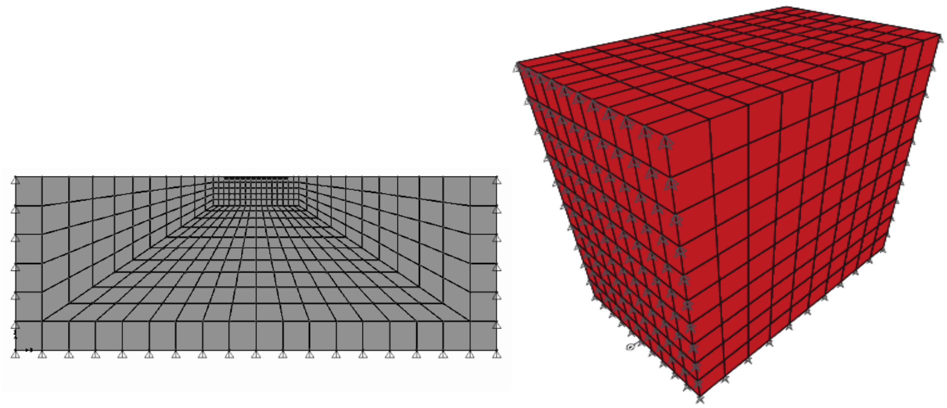


Figure 2: Soil modelling in Lumped Parameter method.

Most of the numerical methods (e.g. FDM and FEM) include an extended form of matrix analysis based on variational approach, where the whole perpetual is divided into a finite number of elements connected at different nodal points. The general principles and use of finite element method and finite difference method is well documented and explained by Desai and Abel (1987). Another well-known numerical method is boundary element method (BEM) which is based on boundary integral equations which presents an attractive computational framework especially for problems involving singularity and unbounded domains. A detailed literature on the formulation of the method and its applications in different fields is addressed in the book by Brebbia *et al.* (1984). The basic idea of this method is to formulate the equation of motion of the unbounded domain in the form of an integral equation instead of a differential equation. Finally, this integral equation is solved numerically. Katsikadelis (2002) indicated that boundary element method has been applied in various areas of engineering and science. However, for many complex problems boundary element method is significantly less efficient than finite element and finite difference methods. Employing numerical methods, researchers are able to model complicated geometries and conditions of soil medium with a high degree of accuracy using two or three dimensional elements (Figure 3).



(a) (b)

Figure 3: Modelling soil medium using numerical methods; (a) 2D model; (b) 3D model.

In the search for a suitable method to model soil structure interactions attention should be drawn to Dutta and Roy (2002) who ascertained that numerical modelling should be employed for its ability to incorporate the effects of non-linear material behaviour, incommensurable material properties, stress anisotropy, material and radiation dampening and geometry changes within the soil from the dynamic soil-structure interaction effects. Therefore, due to the aforementioned capabilities, numerical methods of analysis provide the necessary tools to model many facets of subsoil nonlinearity and structural inelasticity under seismic excitations.

3 EFFECTS OF SSI ON SEISMIC BEHAVIOUR OF BUILDING STRUCTURES

Conventionally the seismic design of structures assumes building frames are fixed at their bases though under seismic loading the supporting sub soil moves due to its natural flexibility. This movement of the supporting soil can be considered to reduce the overall rigidity of the structure, increasing the natural period of the system when compared to a fixed base structure. It was thought by Veletsos and Meek (1974) that as the consideration of SSI led to amplification of the fundamental period of the structure resulting in a higher dampening for the entire soil-structure system, not considering it in analysis would be a more critical case. As explained by Gazetas and Mylonakis (1998) this conclusion was incorrect as in reality amplification of the fundamental period of the system and the influence of soil movements on the structure altered the response in a manner that simply couldn't be ignored. In fact, multiple studies and observations (e.g. Massumi and Tabatabaiefar, 2007; Pitilakis and Terzi, 2011; Fatahi *et al.,* 2014; Tabatabaiefar *et al*., 2015) suggest that neglecting the effects of SSI could lead to the unsafe design of building structures and their supporting foundations leading to catastrophic failure of the structural system, especially when founded on soft soil deposits.

Several researchers (e.g. Veletsos and Prasad, 1989; Balendra and Heidebrecht, 1986; Moss *et al*., 2010; Lu *et al*., 2011) showed that SSI effects are important for medium and long period structures when the predominant site period is large. Recent recorded earthquake spectra demonstrate that SSI will become an important factor for the maximum acceleration occurring at a period greater than 1.0 second. If the fundamental period is lengthened due to soil-structure interaction, the response would be increased rather than decreased, which contradicts the conventional design spectra. Gazetas and Mylonakis (1998) reported three cases of earthquakes, namely, Bucharest 1977, Mexico City 1985 and Kobe 1995, where SSI caused an increase in the seismic-induced response of structures despite a possible increase in damping. They reported that the Mexico earthquake was particularly destructive to l0-12 storey un-braced buildings founded on soft clay, whose period increased from about 1.0s (assumption of a fixed base structure) to nearly 2.0 s due to the SSI. Stewart *et al*. (1998) carried out a comprehensive study including soil-structure interaction effects for 77 strong motion data sets at 57 actual building sites that encompass a wide range of structural and geotechnical conditions. The results of the investigation revealed that inertial SSI effects can be expressed by a fundamental natural period lengthening ratio and foundation damping factor, consequently fundamental natural period of the overall system and total damping will be increased by considering SSI effects. In addition, their research indicated that the period lengthening for long-period structures (T > 2 s) with significant higher-mode responses, maybe negligible. They concluded that approaches proposed by Velestos and Meek (1974) to predict can reliably predict the effect of inertial interaction but are limited to single degree of freedom (SDOF) oscillators. The relationship between the natural period of soil-structure system ($\tilde{T}$) and fixed-base structure (T) proposed by Veletsos and Meek (1974) is as follows:

$$\frac{\tilde{T}}{T} = \sqrt{1 + \frac{k}{k_x}(1 + \frac{k_x}{k_\theta}\frac{h^2}{r^2})} \qquad (1)$$

where, k is the stiffness of the structure, k_x is the lateral stiffness of the subsoil foundation, k_θ is the rocking stiffness of the subsoil foundation, r is the radius of the foundation base (equal to B/2 where B is the foundation width), and h is the height of the structure. Equation (1) denotes that by reducing the soil and foundation parameters such as k_θ and r or increasing the structural characteristics such as k and h, the natural period of soil-structure system ($\tilde{T}$) increases.

The objective of Stewart *et al*. (1998) research concerns the elaboration of a simple procedure for taking into account the influence of the SSI in the determination of the fundamental frequency of buildings. Analyses conducted by Stewart *et al*. (1998) for both one-storey and multi-storey buildings for various geotechnical conditions led to comprehensive charts that give the fundamental frequency of a wide range of buildings in terms of the relative soil-structure stiffness. Research results conducted by Kumar and Prakash (1998) denoted that the fundamental natural period of a soil-structure system reduces nonlinearly with the increase in the soil shear modulus. The effect of considering nonlinear behaviour of the soil on the natural period response of structures depends on the level of strains in the soils. The higher the strain in the soil, the greater is the effect of soil nonlinearity. Kumar and Prakash (1998) have utilised the above mentioned factors (natural period and damping) to derive flexible base fundamental-mode parameters, which are used in response based approaches for evaluating the base shear forces and deformations in structures.

3.1 EFFECT OF SSI ON SEISMIC RESPONSE OF BRACED BUILDING STRUCTURES

According to research conducted by Stewart *et al*. (1999), the structural design of braced framed buildings considering a fixed based support condition was more conservative leading to the conclusion that SSI could be ignored in such circumstances. In the study, two different simulations were performed to assess the behaviour of a steel braced building founded on soft ground with a subsoil shear wave velocity of 190 m/s. Azarbakhti and Ashtiani (2008) conducted a comprehensive numerical analysis for a wide range of braced building frames (Figure 4) with steel brace or shear wall lateral resisting systems in order to evaluate the effects of soil-structure interaction on the seismic structural seismic response. They concluded that considering influence of SSI in seismic design of laterally braced buildings provides a cost effective design since the sections required are smaller in size. Similar conclusions were made by Carbonari *et al*. (2012) after a comprehensive study on nonlinear seismic behaviour of wall-frame systems.

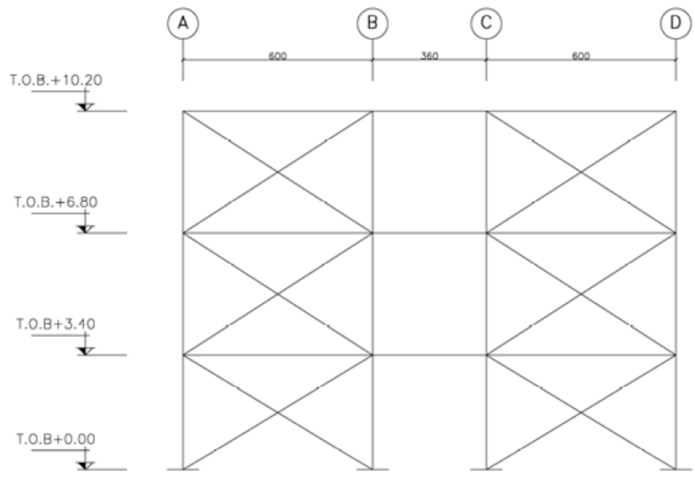


Figure 4: The elevation of the frames under investigation by Azarbakhti and Ashtiani (2008).

It can be concluded that considering effects of SSI in seismic design of the braced building structures will lead to more economic structural sections which means time, energy and cost saving. Therefore, assuming fixed-base structure in accordance with the conventional methods of structural analysis is deemed to be conservative and satisfactory. However, for the sake of design accuracy and cost effectiveness, it might be better always to take SSI into account in seismic design of braced structures.

3.2 EFFECT OF SSI ON SEISMIC RESPONSE OF UNBRACED BUILDING STRUCTURES

According to available research, compared with braced building structures, the effects of SSI on un-braced building frames are considerable. Several studies (e.g. Sivakumaran and Balendra, 1994; Massumi and Tabatabaiefar, 2007; Galal and Naimi, 2008; Tavakoli *et al*., 2011, Tabatabaiefar and Mansoury, 2015) have reported that SSI can amplify the lateral deflections and corresponding inter-storey drifts of structures founded on soft grounds. The rigidity of the supporting soil medium plays a crucial role in the seismic behaviour and response of the structural system (Tabatabaiefar, 2012b). Structures supported by soils which have enough stiffness to significantly reduce the soil-structure interaction maybe analysed with a fixed base support condition. If, however, the supporting soil medium is soft, its flexibility can cause significant interactions between the structure and soil during an earthquake event. Research conducted by Veletsos and Meek (1974) determined that "*when the shear wave velocity of the supporting soil was less than 600 m/s, the effects of soil structure interaction was considerable*." This assumption has since been adopted by many other researchers solving soil interaction problems.

Galal and Naimi (2008) conducted a comprehensive numerical study on un-braced building frames up to 20 stories under the influence of SSI founding on site classes B, C, D, and E according to site classifications of International Building Code (IBC 2009). IBC2009 site subsoil classifications are presented in Table 1. Based on their study results, when supporting rock or very dense soil exists (site class A, B and C), the structure can be assumed as fixed base. For tstructures constructed on other softer soils with shear wave velocity less than 600 m/sec comprising site class E, D and lower limit of C (360 m/s < Vs < 600 m/s), overall structural response might be affected by soil-structure interaction, while for the structures resting on site classes A, B, and upper limit of soil C (600 m/s < Vs < 750 m/s), SSI effects on structural response would be negligible. Thus, in order to find reliable and accurate results, soil-structure interaction effects should be taken into consideration in dynamic analysis of the structures resting on site class E, D and lower limit of C.

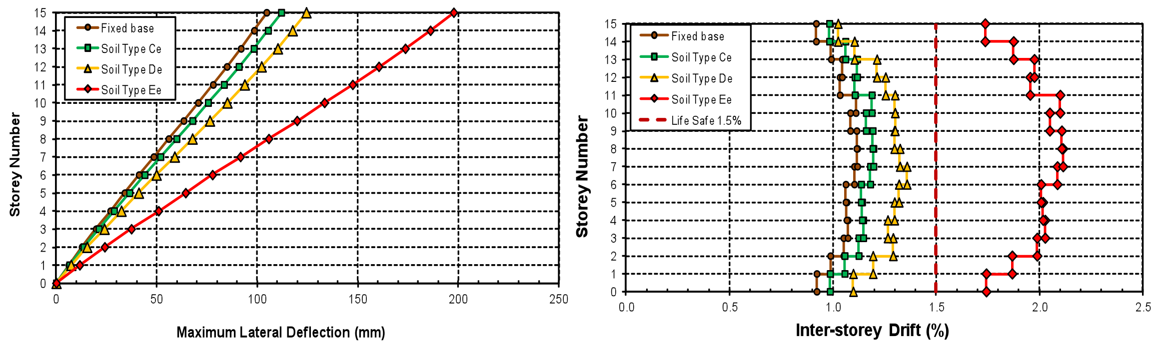
Table 1: Site subsoil classifications according to IBC2009

Site Class	Soil profile name	Soil shear wave velocity V_s(m/s)	Soil undrained shear strength, S_u (KPa)	Standard Penetration Resistance (*N*)
A	Hard Rock	1500> Vs	N/A	N/A
B	Rock	750 < Vs < 1500	N/A	N/A
C	Very dense soil	360 < Vs < 750	S_u > 100	N > 50
D	Stiff soil profile	180 < Vs < 300	50 < S_u < 100	15 < N < 50
E	Soft soil profile	Vs < 180	S_u < 50	N < 15

El Ganainy and El Naggar (2009) studied seismic behaviour of unbraced building frames resting on subsoil classes C (360 m/s < Vs < 750 m/s) and E (Vs < 180 m/s) in accordance with IBC2000 under the influence of SSI. They concluded that structural deformations of the buildings were substantially influenced by soil-structure interaction. Lateral deformations of the buildings with flexible bases, experienced considerable amplification ranging from 50% to about 300% in comparison to the fixed bases for buildings founded on soil class E (Vs < 180 m/s).

Tavakoli *et al*. (2011) after conducting a comprehensive numerical study on moment resisting building frames elucidated that, in general, as the soil under the structure becomes softer, SSI influences lateral deflections, inter-storey drifts, base shear, period of the structure and earthquake field effects more significantly. According to their results, the importance of soil-structure interaction could be neglected for unbraced building frames resting on rock or very stiff soil while considering SSI for structures supported on relatively soft soil is necessary.

Tabatabaiefar *et al*. (2013) conducted extensive numerical investigation on a full range of mid-rise un-braced building structures founded on three soil classes of C_e, D_e and E_e according to the soil classification of AS1170.4 with shear wave velocities less than 600m/s. The results of their numerical investigations showed that SSI intensely affects seismic behaviour of mid-rise unbraced building structures constructed on subsoils with shear wave velocity of less than 320 m/s (Figure 5).



(a) (b)

Figure 5: Example of the average results of dynamic analyses of a 15 storey building for two cases of fixed base and flexible base models resting on three different subsoils; (a) Lateral deflections; (b) Inter-storey drifts (Tabatabaiefar *et al.*, 2013)

As a result, seismic design of those building frames without considering dynamic soil-structure interaction may not be risk free. Following this study, Tabatabaiefar *et al.* (2014a) performed comprehensive experimental shaking table tests on a physical soil-structure scaled model (Figure 6) to validate their numerical results and to experimentally investigate the nature of SSI on seismic behaviour of unbraced building frames founded on soft soil deposits.

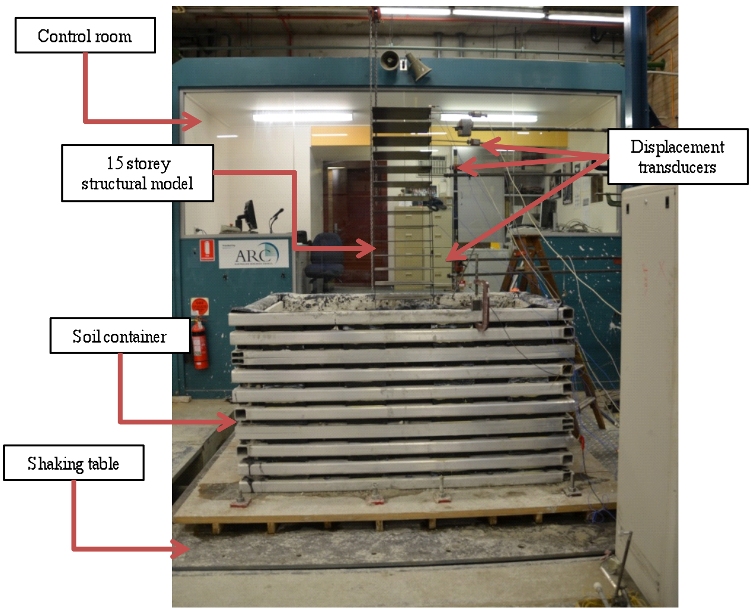


Figure 6: Physical soil-structure scaled model to validate their numerical results and to experimentally investigate (Tabatabaiefar *et al.*, 2014a)

The experimental results revealed profound amplification of the lateral deflections and corresponding inter-storey drifts for unbraced buildings resting on soils with shear wave velocity of less than 320 m/s. As a result, "buildings performance levels change extensively (e.g. from life safe to near collapse level), which can be extremely dangerous and safety threatening. Thus experiment shows that SSI plays a significant role in seismic behaviour of unbraced building frame resting on relatively soft soils."

4 EMPERICAL RELATIONSHIPS FOR CONSIDERING SSI EFFECTS IN SEISMIC DESIGN OF UNBRACED BUILDING STRUCTURES

Several researchers attempted to formulate the effects of the SSI on the seismic response of unbraced buildings. Veletsos and Meek (1974) proposed a simple criterion indicating that when considering the effects of soil-structure interaction it is necessary to take into account soil shear velocity, natural frequency of fixed base structure and total height of the structure. The specific objectives of the mentioned contribution were to identify the parameters which best describe the interaction effects and evaluate these effects in order to define the conditions under which they are of sufficient importance to warrant consideration in design. In addition, Veletsos and Meek (1974) presented a basic equation to determine the ratio of the maximum lateral deflection of the structure in the soil-structure system ($\widetilde{\delta}$) to the maximum lateral deflection of fixed base structure (δ) as follows:

$$\frac{\widetilde{\delta}}{\delta} = \left(\frac{f}{\widetilde{f}}\right)^2 \tag{2}$$

where, $\widetilde{f}$ is the natural frequency of soil-structure system and f is the natural frequency of fixed base structure. In spite of the fact that the proposed equation has been extracted from a rigorous analytical procedure, it is not directly suitable for practical purposes. In order to determine the maximum lateral deflection of the structure in the soil-structure system ($\widetilde{\delta}$), the natural frequency of fixed base structure (f), the maximum lateral deflection of fixed-base structure (δ), and the natural frequency of soil-structure system ($\widetilde{f}$) should be available. The first two parameters can be found directly from analysing the fixed base structure but the third one ($\widetilde{f}$) can be determined only after undertaking full dynamic soil-structure interaction analysis and designing the structural sections. As a result, Equation (2) cannot be individually utilised as empirical relationship for determining seismic response of structures under the influence of soil-structure interaction.

In order to overcome this shortcoming, Tabatabaiefar *et al*. (2014b) carried out comprehensive numerical parametric studies. After rigorous regression analyses of the outcomes, they proposed the following empirical relationship to determine the lateral storey deflections of un-braced building frames under the influence of SSI:

$$\widetilde{d}_i = d_i\left(1 + \frac{h^2 h_s E_{str}}{\lambda \rho V_s^2 B^3}\right) \tag{3}$$

where, h is the height of the structure, B is the foundation width, ρ is the soil density, V_s is the shear wave velocity of the subsoil, E_{str} is the modulus of elasticity of the structural material, λ is Analysis Type Factor (for elastic analysis and for inelastic analysis), $\widetilde{d}_i$ is the lateral storey deflection at *(i)* level under the influence of SSI and d_i is the lateral storey deflection at *(i)* level for the fixed base structure (without SSI effects).

For practical purposes, the maximum lateral deflections for each storey under the influence of SSI can be extracted from Equation (3). Then, inter-storey drifts under the influence of soil-structure interaction for each two adjacent stories can be determined and checked against the limiting value of 1.5% for life safe performance level. Thus, detrimental effects of soil-structure interaction may be more accurately taken into account in the seismic design of mid-rise moment resisting building frames to ensure the design is safe and reliable. The simplified procedure described in this section can be used by structural engineers and engineering companies, as a reliable and accurate method of considering SSI effect in the seismic design procedure (Tabatabaiefar *et al*., 2014b).

4.1 WORKED EXAMPLE

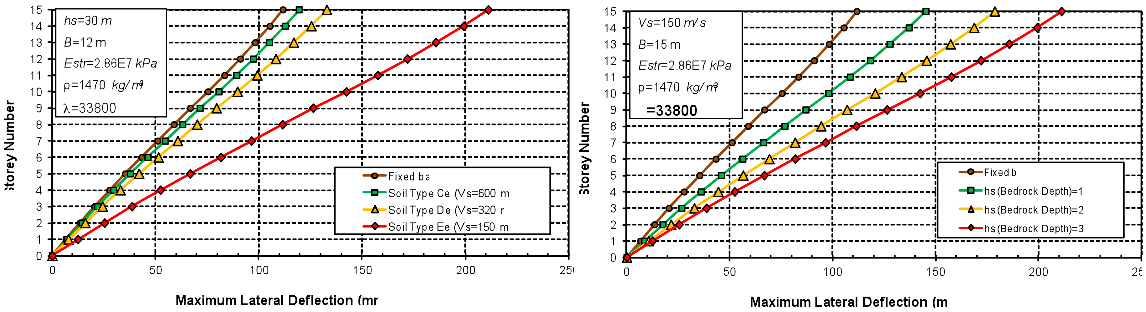
In order to use Equation (3) for practical purposes, structural engineers should first determine the maximum lateral deflections for each level (d_i) from dynamic analysis of the fixed based model. Then, by having d_i values for each level and determining the site and structural characteristics including the shear wave velocity of the subsoil (V_s), the bedrock depth (h_s), the height of the structure *(h)*, the foundation width (B), the soil density (ρ), the modulus of elasticity of the structural material (E_{str}), and appropriate analysis type factor (λ), the lateral storey deflections for each level under the influence of SSI ($\widetilde{d}_i$) can be estimated from Equation (3).

In this section, as a worked example of using the proposed simplified design procedure, a 15 storey intermediate moment resisting building frame 45 m high and 12 m wide (h = 45 m and B=12 m) with structural ductility factor (μ) of 3 and performance factor (S_p) of 0.67 has been selected. Soil density (ρ) of 1470 kg/m^3 and the modulus of elasticity of concrete (E_{str}) equal to 28600 *MPa* have been adopted. Dynamic analysis is performed on the fixed base model adopting conventional elastic analysis procedure (λ=33800) and the results of dynamic analysis in terms of maximum lateral deflections for each storey are derived and presented in Figure 7 as the fixed base results. The fixed base results represent the lateral storey deflections at level *i* for the fixed base structure (d_i) in Equation (3). Having d_i values for each storey as well as the height of the structure *(h)*, the foundation width (B), the soil density (ρ), the modulus of elasticity of the structural material (E_{str}), and analysis type factor (λ), the lateral storey deflection at level *i* under the influence of SSI ($\widetilde{d}_i$) are determined for each storey using Equation (3) for the following cases:

- Variable shear wave velocities for the subsoil adopting soil classes C_e, D_e, and E_e (Figure 7a) assuming the bedrock depth of 30 m and

- Variable bedrock depths including h_s=10 m, 20 m, and 30 m adopting shear wave velocity of the subsoil equal to 150 m/s (Figure 7b).

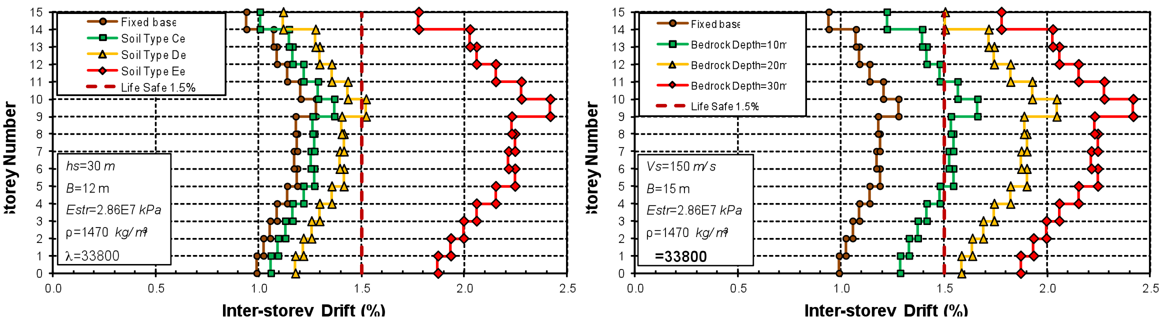
Figure 7 illustrates the calculated lateral storey deflections at each level under the influence of SSI ($\widetilde{d}_i$), obtained from Equation (3) for two mentioned cases.



(a) (b)

Figure 7: (a) Determined lateral storey deflections at each level for 15 storey building resting on soil classes C_e, D_e, and E_e; (b) Determined lateral storey deflections at each level for 15 storey building resting on soil class E_e with variable bedrock depths.

Having the lateral storey deflections, the corresponding inter-storey drifts under the influence of soil-structure interaction for each two adjacent stories have been determined (Fig.8). It is now possible to check the inter-storey drifts of the building frame against the limiting value of 1.5% for life safe performance level.



(a) (b)

Figure 8: (a) Inter-storey drifts for 15 storey building resting on soil classes C_e, De, and E_e; (b) Inter-storey drifts for 15 storey building resting on soil class E_e with variable bedrock depths.

Inter-storey drifts, shown in Figure 8, clearly illustrate that by reducing the shear wave velocity of the subsoil or increasing the bedrock depth, performance level of the 15 storey un-braced building frame changes from life safe to near collapse level when SSI is considered in the analysis, which is dangerous and safety threatening. According to Tabatabaiefar *et al*. (2014b), using the proposed simplified method, it can be ensured that performance levels of the un-braced building frames under the influence of SSI remain in life safe level, and the seismic design is safe and reliable.

5 CONCLUSIONS

The current study carries out a comprehensive critical review on available and well-known research studies in the area of seismic behaviour of braced and un-braced building structures affected by soil-structure interaction (SSI). Based on the results of the current review, it has become apparent that considering effects of soil-structure interaction in seismic design of the braced building structures will lead to more economic structural sections which means time, energy and cost saving. Therefore, assuming fixed base structure based on the conventional methods of structural analysis is deemed to be conservative and adequate to guarantee the structural safety. However, for un-braced building frames constructed on grounds with soil shear wave velocity of less than 320 m/s, SSI extremely affect seismic behaviour of un-braced buildings by amplifying lateral deflections and corresponding inter-store y drifts forcing the structural performance level to change from life safe to near collapse or total collapse. As a result, conventional seismic design procedure of un-braced building frames resting on soft grounds without taking into account detrimental effects of dynamic soil-structure interaction cannot adequately assure structural sufficiency and safety for the benefit of the community.

In order to consider the amplification of lateral deflections and corresponding inter-storey drifts under the influence of soil-structure interaction in seismic design of un-braced building frames, a simplified design procedure has been introduced and elucidated. The design procedure enables structural engineers to determine inter-storey drifts under the influence of soil-structure interaction for each two adjacent stories and check those drifts against the limiting value of 1.5% for life safe performance level. Thus, detrimental effects of soil-structure interaction can be captured more precisely in the seismic design procedure of un-braced building frames to ensure the design safety and reliability.

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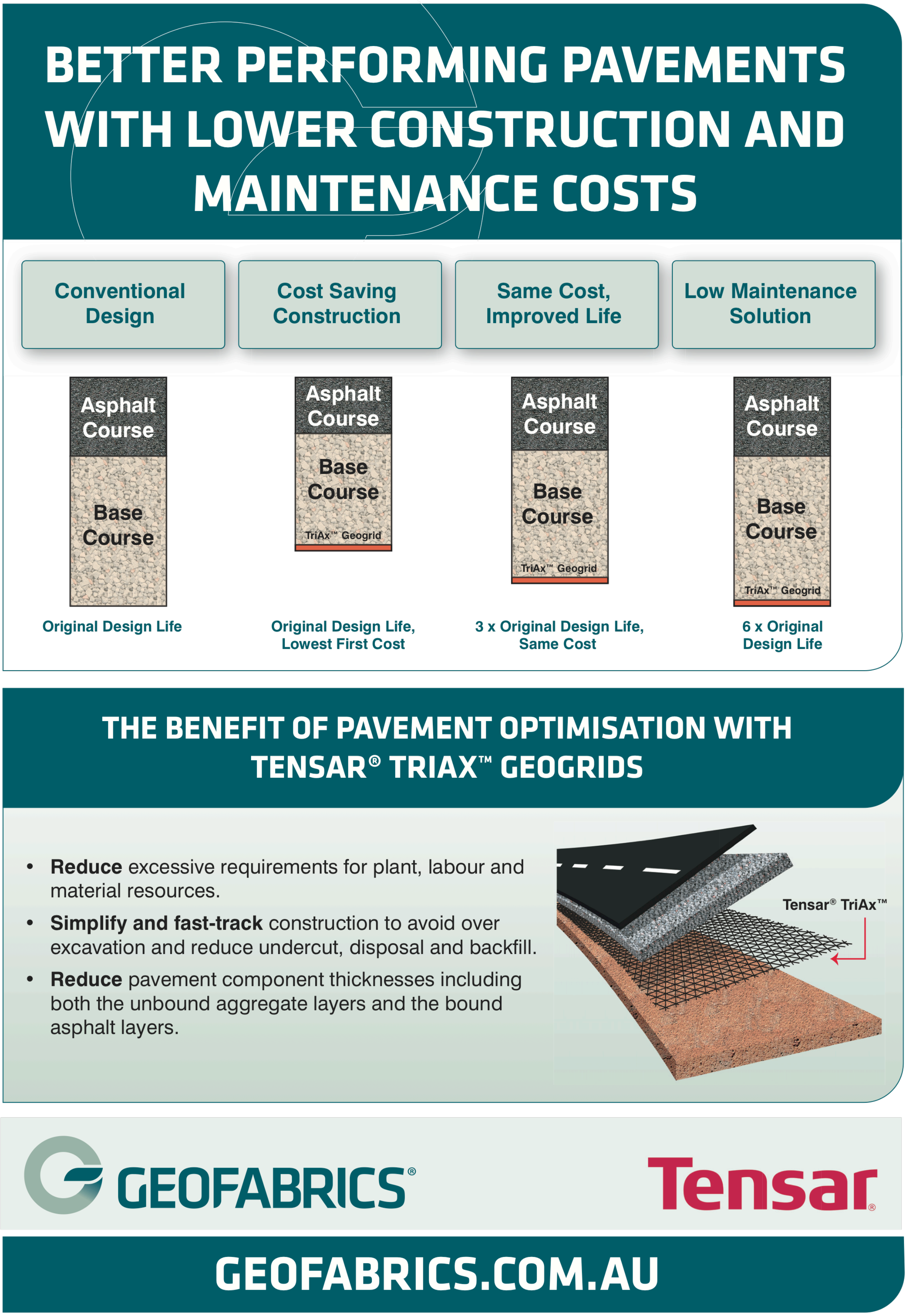

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